Expected luminosity improvement with electron cooling

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Beam dynamics luminosity limits for RHIC operation at low energies

On top of dynamic aperture limitation

at lowest energies in RHIC

some fundamental limitations come from:

See for details:
Proc. of PAC11: THP081,
C-A/AP/421, C-A/AP/435

Intra-beam Scattering (IBS):

- **Strong IBS growth at lowest energies- can be counteracted by Electron cooling**

Beam-beam:

- **Becomes dominant limitation for RHIC parameters at $\gamma > 20$**

Space-charge:

- **At lowest energies, ultimate limitation on achievable ion beam peak current is expected to be given by space-charge effects (note: not the same as typical space-charge limit in low-energy machines or space-charge dominated beams)**

Luminosity limitation by space-charge and beam-beam

Luminosity expressed through

beam-beam parameter ξ:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^* C} \frac{2\gamma\beta^3}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

$$\xi = \Delta Q_{bb} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma\varepsilon} \frac{1+\beta^2}{2}$$

Luminosity expressed through

space-charge tune shift ΔQ_{sc}:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^*} \frac{\sqrt{2\pi}\sigma_s}{C^2} \gamma^3\beta^3 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q_{sc}$$

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{1}{B_f}$$

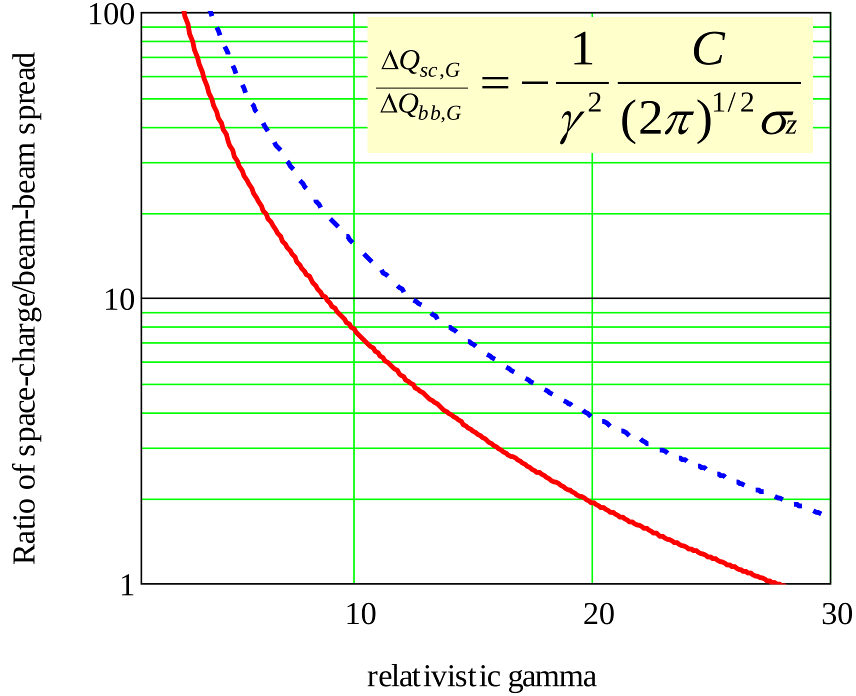


Figure 1: Ratio of space-charge tune spread to beam-beam spread (for heavy ions) at low energies in RHIC for rms bunch length 2 m (red) and 1 m (blue, upper dash line).

What is acceptable space-charge tune shift for long beam lifetime with collisions?

Available theoretical and experimental knowledge about independent limitation due to the space-charge or beam-beam effects is extensive and provides useful guidelines, but interplay of both effects was largely unexplored.

Series of dedicated experimental studies were done at RHIC:

- **Accelerator Physics Experiments (APEX) May and June 2009:**

p+p: at beam γ=25 (modest space-charge, large beam-beam)

- **APEX March 2010:**

Au+Au ions: γ=10.5 (modest space-charge, small beam-beam)

- **Several APEX and Low-Energy RHIC run May - June 2010:**

Au+Au ions: γ=6.1 and γ=4.1 (large space-charge, small beam-beam)

- **APEX 2011 (small and large beam-beam, near integer w.p.)**

Measured beam lifetime (without collisions)

Table 1. Overview of several experiments (without collisions).

ΔQ_{sc} (x,y)	τ [s]	γ	Comments
0.03	2000	10	$5\sigma_x$ acceptance, Q_s=0.002, no attempt for other w.p.
0.05, 0.04	1600	6.1	>$3\sigma_x$ acceptance, Q_s=0.006
0.085, 0.065	700	6.1	>$3\sigma_x$ acceptance, Q_s=0.006
0.1	70	4.1	$2.2\sigma_x$acceptance, Q_s=0.013

During 2009-12 several dedicated APEX experiments were done to study beam lifetime with large space charge spread and different beam-beam parameters.

For details see
Proc. of HB10: THO1C03;
Proc. of PAC11: THP081

Table 2. Best observed beam lifetimes for significant space charge (without collisions).

ΔQ_{sc}	τ	γ	Comments
0.02	> 6 h	10	Both rings
0.027-0.029	5/3h	10	Yellow/Blue
0.035	~2h	10	Yellow only, w.p. near integer

Lifetime was improved by moving to a working point near integer.

RHIC experience

Beam lifetime without collisions (γ=6.1, RHIC Run-10)

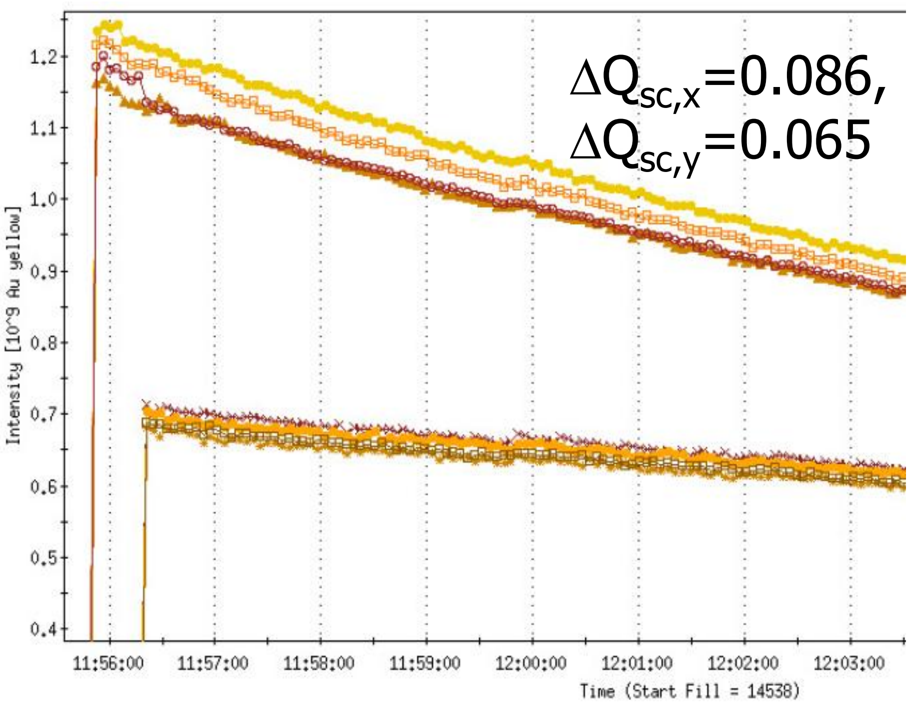


Figure 2: Intensity (x10^9) evolution of several bunches at γ=6.1 without collisions.

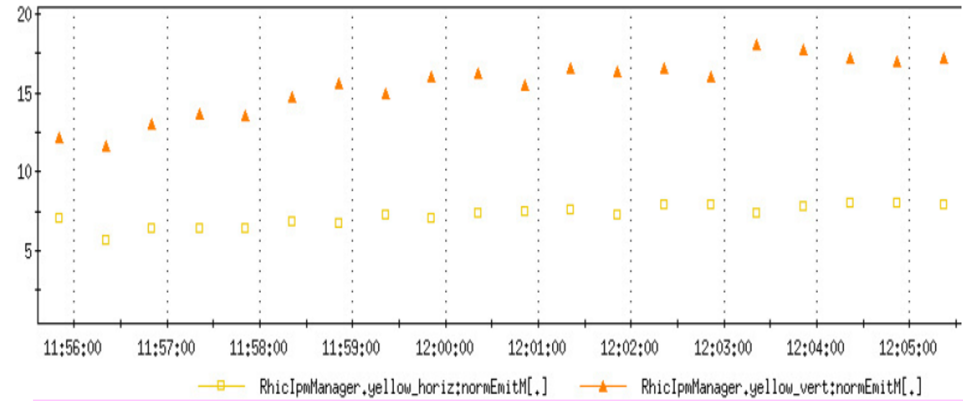


Figure 3: Vertical axis: horizontal and vertical emittance (95% normalized μm) for beam in Yellow ring without collisions at γ=6.1; horizontal axis: clock time.

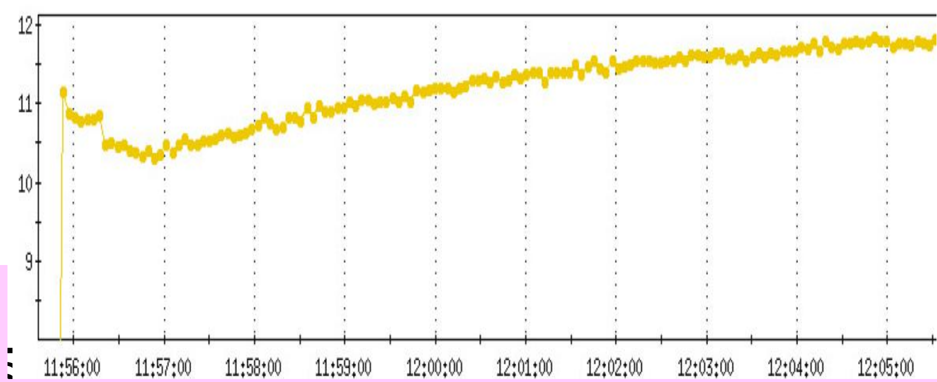


Figure 4: Bunch length (WFHM [ns]).

Intensity dependent effects without collisions: at γ=6.1 vs. γ=4.1

For the same space-charge tune spreads (used here as intensity parameter), fast component of beam lifetime:

1. ΔQ_{sc} value close to 0.1: 100 s (γ=4.1), 750 s (γ=6. 1)
2. ΔQ_{sc} value around 0.05: 300 s (γ=4.1), 1600 s (γ=6.1)

Transverse acceptance (collimators: 2 (γ=4.1) vs. 3 sigma (γ=6. 1)).

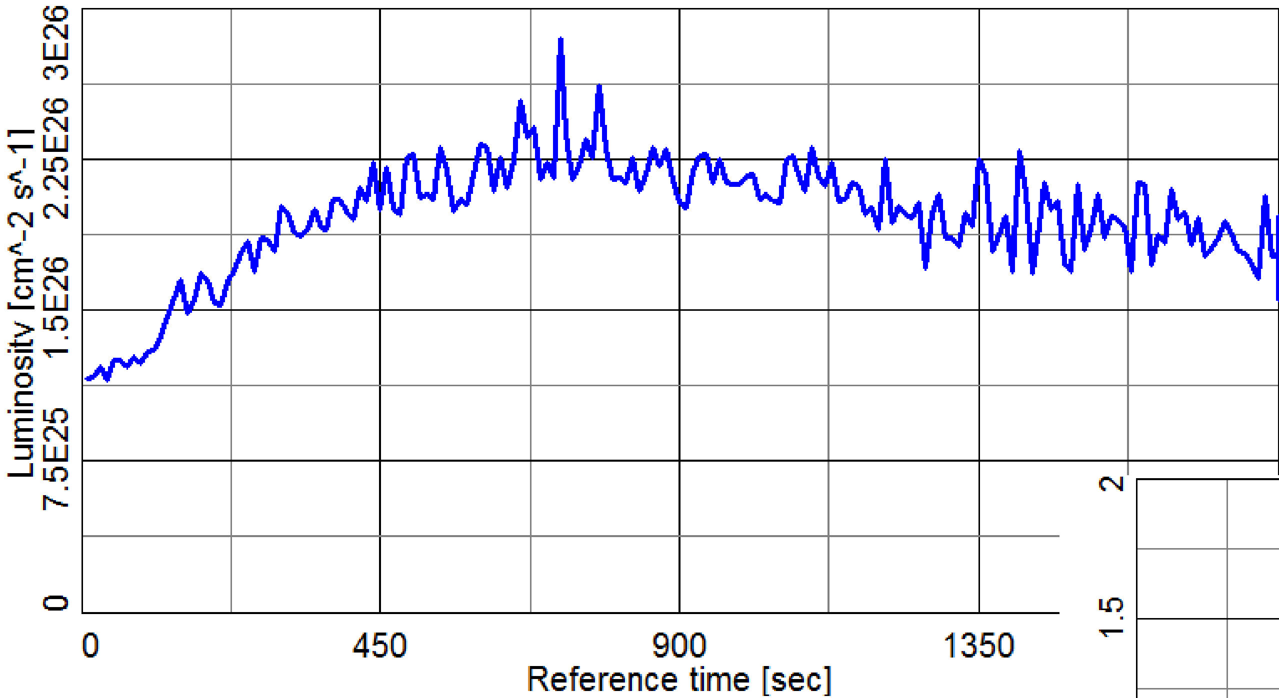
Without aperture limitation (higher energy γ=10) and working point close to an integer, lifetime of >2 h was measured for ΔQ_{sc}=0.035.

- To have improvement from cooling below γ=6.1:

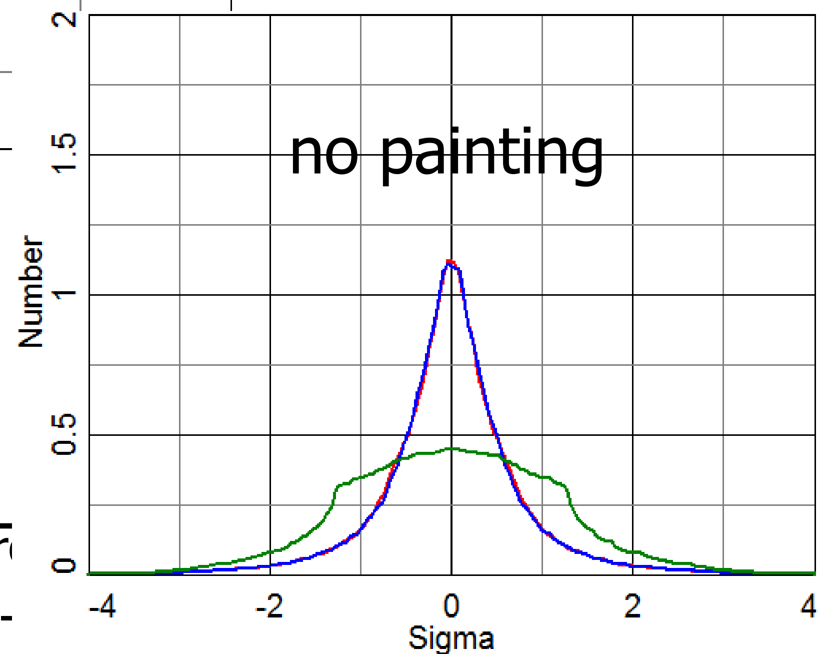
- need more transverse acceptance (> 3*sigma)
- try to limit space-charge tune spread to 0.05 or less (not very strict)
- have beams with smaller dp/p

Proposed operation with long bunches (low-frequency RF: 4.5 MHz) together with e-cooling addresses these issues.

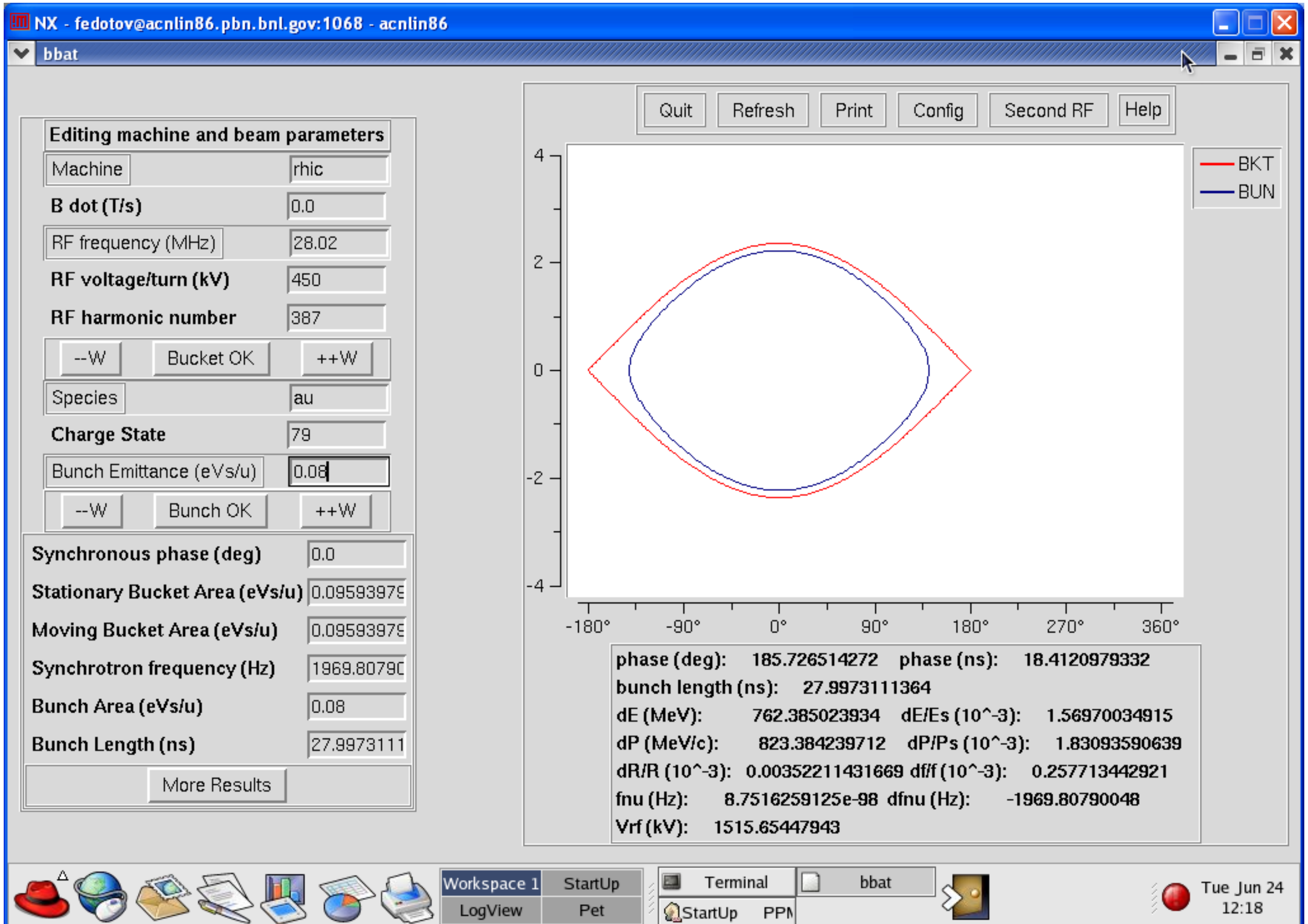
28 MHz high energies from BES-II (γ=10.7)
Luminosity with cooling: using 2 electron bunches with Q_e=2.5nC/per bunch)



γ=10.7
(28 MHz RF)

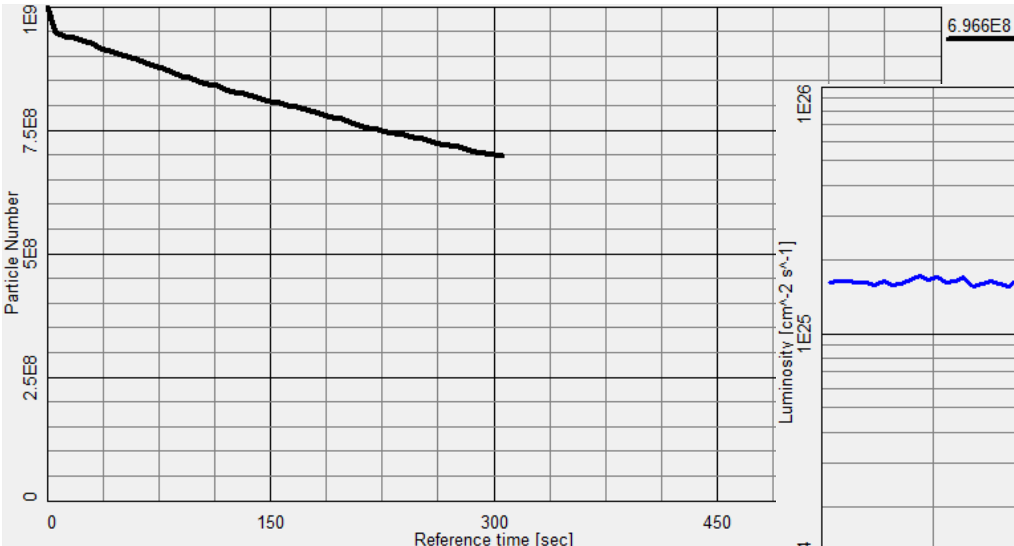


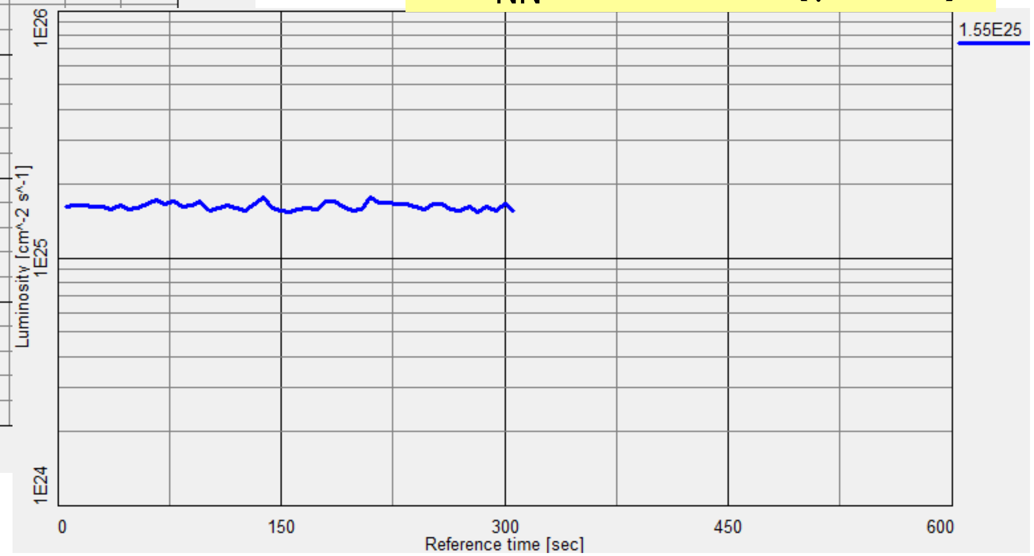
28 MHz RF has limited acceptance for lowest energies from BES-II request (for example, 0.1 eV-s for γ=2.7 with emittance emittance S_95%=0.1 eV-s or larger).

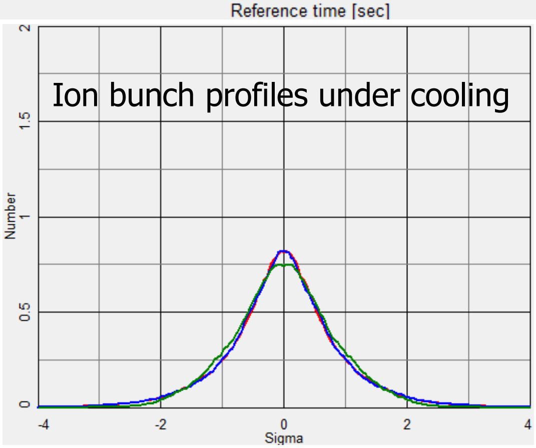


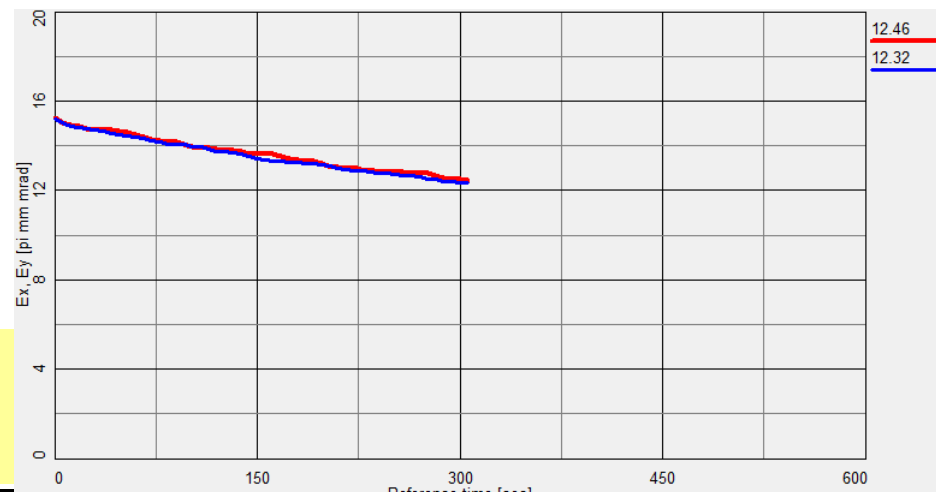
28 MHz RF low energies from BES-II request (γ=4.1)
Cooling with strong losses from RF bucket

$\sqrt{s_{NN}}$ =7.7 GeV (γ=4.1)









For intensity loss from RF bucket we keep luminosity constant by cooling transverse emittance, at some point can even decrease beta*.

Potential for luminosity improvement with longer bunches

For present 28 MHz RF at lowest energies we are limited both by space charge and RF bucket acceptance (significant beam losses), which strongly limits luminosity improvement with cooling.

Additional gain in luminosity is possible if one can tolerated operation with longer bunches for lowest energies:

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A}\frac{N_i}{4\pi\beta^2\gamma^3\varepsilon}\frac{C_r}{\sqrt{2\pi}\sigma_s}$$

If bunch length is relaxed, we can now cool transverse emittance which in turn allows to reduce β*. Losses on transverse acceptance will be minimized as well.

Luminosity limitation by space charge

$$L = \frac{N_i^2}{4\pi\varepsilon\beta^*} F_{coll}\, f\left(\frac{\sigma_s}{\beta^*}\right)$$

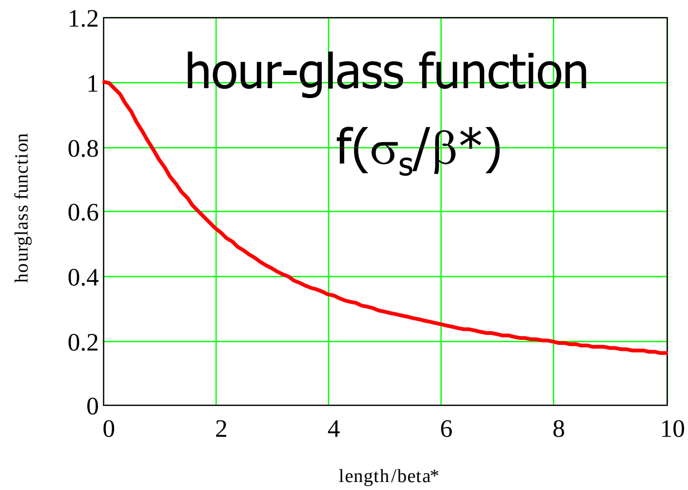
Luminosity expressed through space-charge tune shift ΔQ_{sc}:

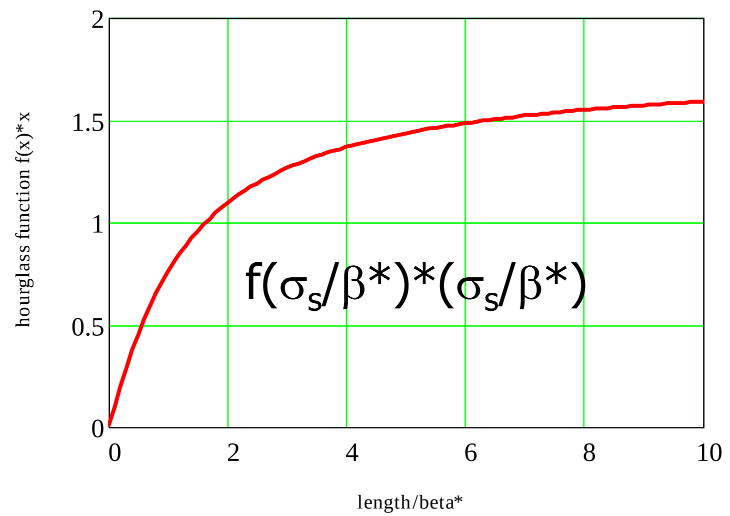
$$L = \frac{A}{Z^2 r_p} \frac{\sqrt{2\pi} N_i c}{C_r^2} \gamma^3 \beta^3 \frac{\sigma_s}{\beta^*} f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q_{sc}$$

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{C_r}{\sqrt{2\pi}\sigma_s}$$

When also limited by transverse acceptance (which is the case for RHIC lowest energy points):

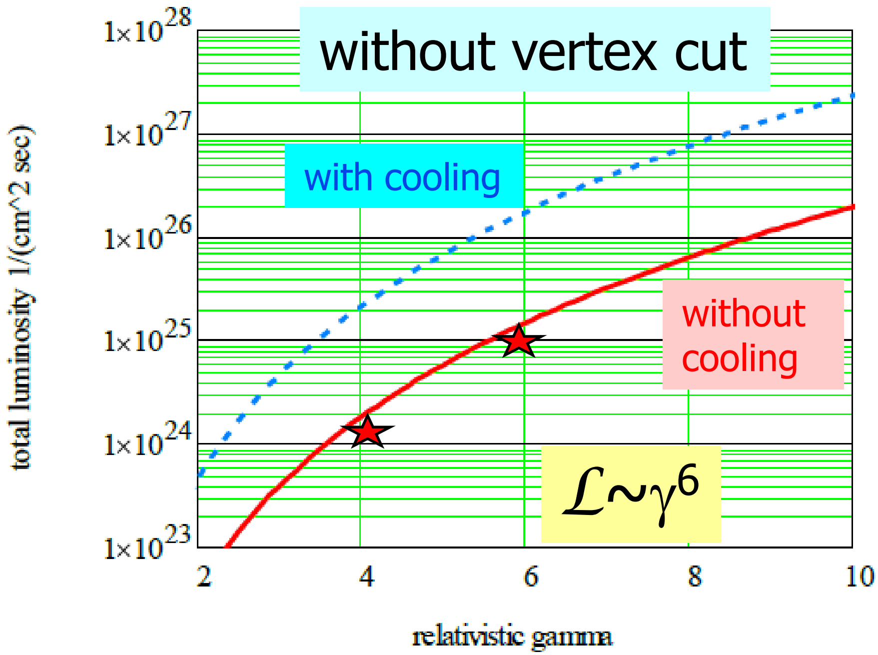
$$L = 8\pi^2 \left(\frac{A}{Z^2 r_p}\right)^2 \frac{c\varepsilon}{\beta^*} \frac{\sigma_s^2}{C_r^3} \gamma^6 \beta^5 f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q_{sc}^2$$





Projection (maximum possible or “ideal”) for luminosity improvement low-frequency RF (4.5 or 9MHz) and long bunches

C-A/AP/449 (for details)



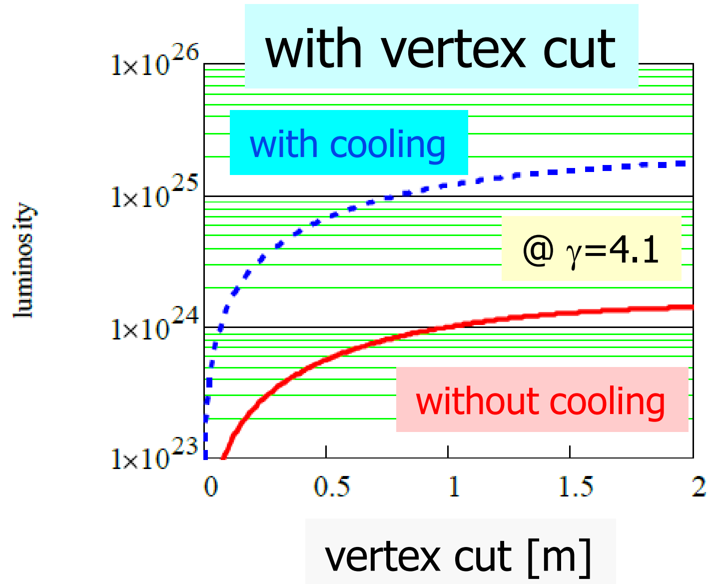


Fig. 6. Average luminosity for 111 bunches of Au ions in RHIC at γ=4.1

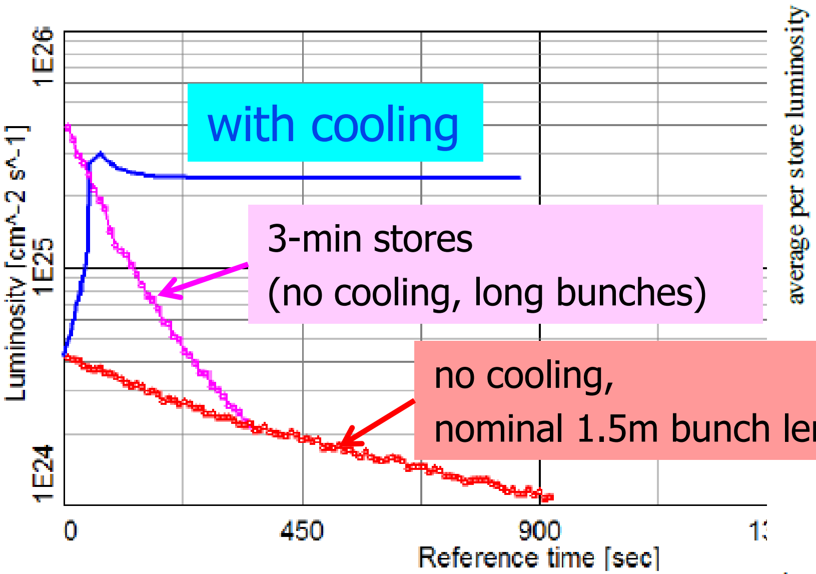
Example for 9 MHz RF

Fig. 8. Projection of total (without vertex cut) luminosity for 111 bunches of Au ions in RHIC for the space-charge tune spread of ΔQ_{sc}=0.05 with electron cooling and long bunches (blue, dash upper curve) and without cooling (red, solid lower curve).

Up to about factor of 10 gain in total luminosity for all low energies with longer bunch length may be expected from electron cooling (*assuming that beam lifetime due to other limitations is mitigated).

Luminosity lifetime

Example for γ=4.1, 9 MHz RF ($\sqrt{s_{NN}}$ = 7.7 GeV):



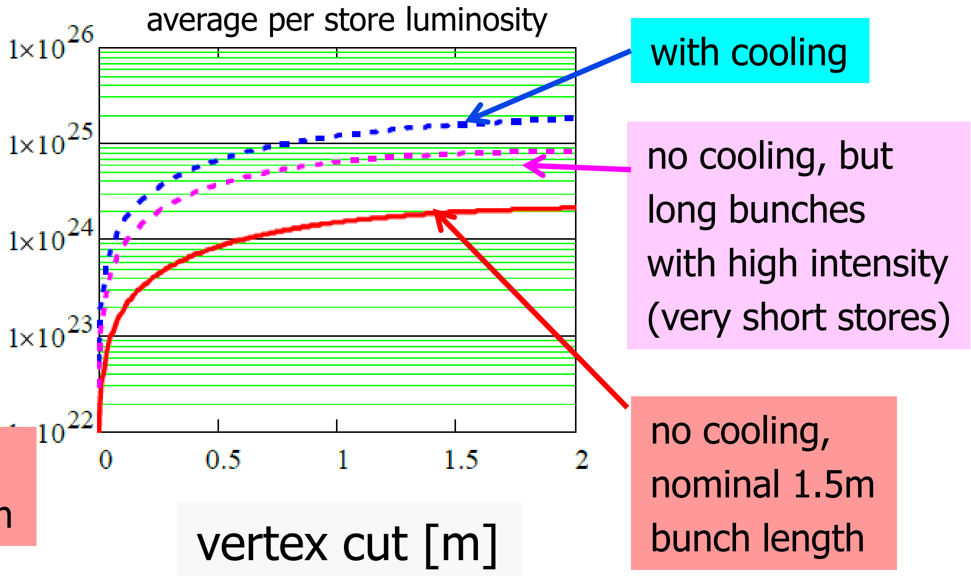
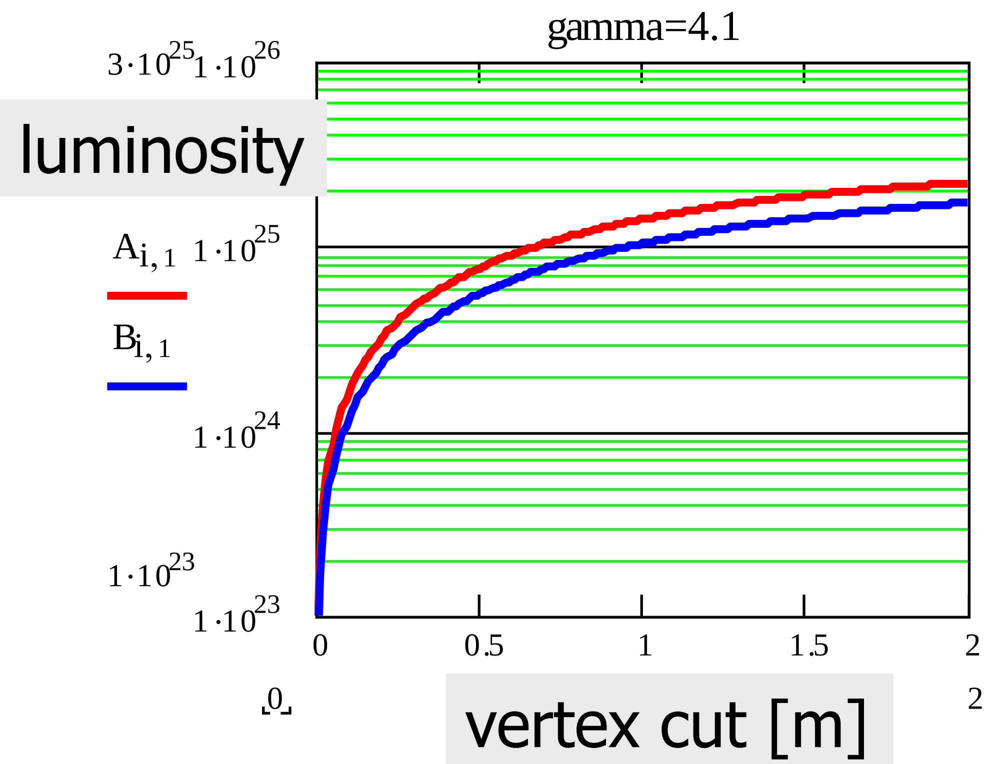


Fig. 9. Average (per store) luminosity for 111 bunches of Au ions in RHIC at γ=4.1

Fig. 10. Simulated luminosity evolution for 3 cases summarized in Fig. 9: 1) electron cooling and long bunches (σ_s=4.5 m, β^*=2 m, $\varepsilon_{n,95\%}$=5 μm, N_i=5e8) – blue, top curve; 2) without cooling (σ_s=1.5 m, β^*=6 m, $\varepsilon_{n,95\%}$=15 μm, N_i=5e8) – red; 3) without cooling but longer bunches with higher bunch intensity (σ_s=4.5 m, β^*=6 m, $\varepsilon_{n,95\%}$=15 μm, N_i=1.5e9) – magenta.

Selected new RHIC RF system



Luminosity of cooled beams:

Red – 9 MHz (55ns full length)

Blue – 4.5 MHz (100ns full length)

We selected 4.5 MHz as baseline, to simplify design due to smaller voltage required.

C-A/AP/476 (for details)

By going from 120 bunches (9 MHz) to 60 bunches (4.5 MHz) we loss factor of two in luminosity. This is recovered by increasing bunch intensity.

Bunch length of 6 m rms (4.5 MHz) vs 3 m (9 MHz) may appear to reduce useful luminosity within detector +/-1m significantly. However, keeping the same space-charge tune shift, longer bunches allow us to cool emittance stronger and reduce beta* accordingly. Resulting luminosities with both RF systems are thus comparable (apart for hour-glass factor).

Long bunches and IBS (see AP Note 477 for details)

Choosing lower frequency RF system and thus longer bunches will reduce space-charge tune spread value. This will allow to cool beam transversely which in turn should allow us to reduce beta-function at the interaction point resulting in higher luminosity [8]. In addition, transverse cooling will enable larger transverse acceptance which should provide better beam lifetime for the same space-charge tune spread value, as observed experimentally [4-5]. However, longer ion bunch will have smaller momentum spread and thus stronger longitudinal IBS growth rates.

$$\frac{d\sigma_p^2}{dt} = \frac{r_i^2 c N_i \Lambda_c}{8\beta^3\gamma^3\varepsilon_{x,un}^{3/2}\left\langle\beta_x^{1/2}\right\rangle\sigma_s}\left(1-\sqrt{\frac{\Delta_z}{\Delta_x}}\right)$$

For longitudinal temperature < transverse

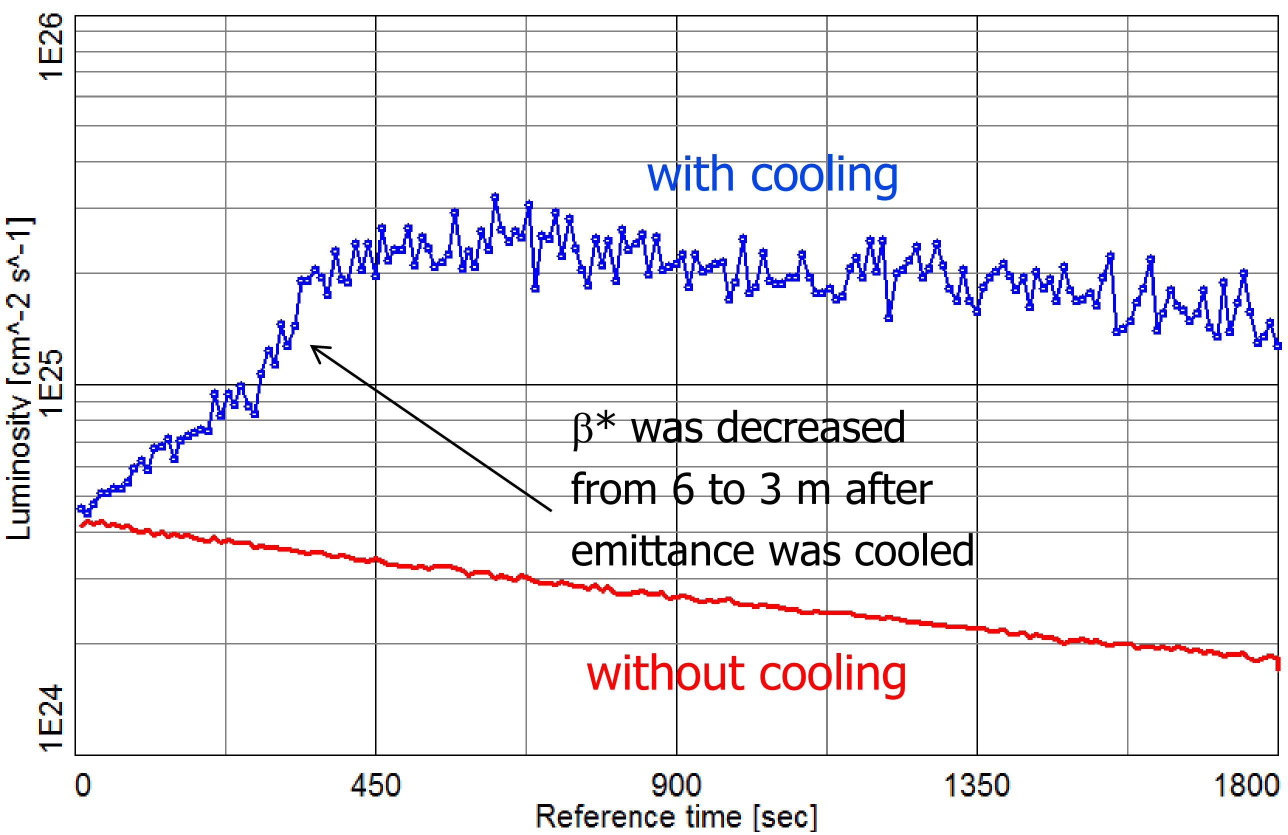
Would need to operate with large longitudinal emittances.

S_{95}, eV-s/n	RF bucket acceptance A_s, eV-s/n	RF Voltage, kV	σ_p	σ_s, m	ΔQ_{sc}	transverse IBS τ_x^{-1}, sec^{-1}	longitudinal IBS τ_z^{-1}, sec^{-1}
0.15	0.46	10	0.00012	5.35	0.02	-0.0007	0.064
0.4	0.8	30	0.00026	6.6	0.016	-0.00006	0.006
0.4	1.0	50	0.00029	5.8	0.019	0.00001	0.005
0.5	1.3	80	0.00036	5.8	0.019	0.00016	0.0026

Table 5. IBS rates ($\tau_x^{-1}=d\varepsilon_x/\varepsilon_x dt$, $\tau_z^{-1}=d\sigma_p^2/\sigma_p^2 dt$) for bunch intensity of N=7.5e8 for 4.5 MHz RF, γ=4.1 and transverse beam emittance of ε=15 μm (95%, normalized).

<u>γ@4.1</u> (sqrt[s]=7.7 GeV), Simulations assuming new 4.5 MHz RHIC RF system

- **Luminosity (simulations) with longer bunches (4.5 MHz)**

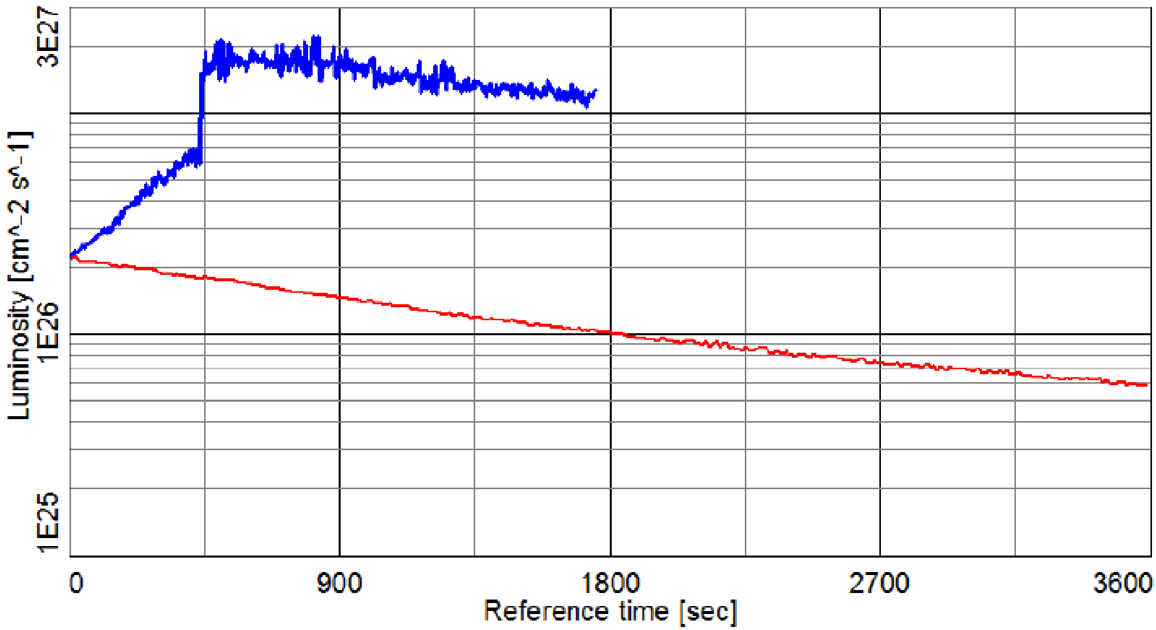


Initial bunch parameters:
N=0.75e9,
σ_s=5.8 m (rms length)
ΔQ_{sc}=0.019 (space-charge spread)

Allows to cool transversely and decrease β*.

Even larger luminosity than shown since we should be able to start with smaller β* from the beginning.

γ@10.7 (sqrt[s]=20 GeV)
(can use both new 4.5 and present 28 MHz RHIC RF)



Better luminosity improvement is expected for higher energy points of proposed BES-II, since we do not have strong limitation from space charge or physical/dynamic aperture.

Figure 2. Luminosity at γ=10.7 and 28 MHz RF (450 kV) for initial β*=3m, 111 bunches with $1.5\cdot 10^9$ bunch intensity and transverse 95% normalized emittance of 15 mm mrad. Red curve: IBS and losses from RF bucket only; blue curve: IBS, losses from RF bucket and electron cooling.

Radiative recombination of heavy ions with electrons

$$A^{Z+} + e^- \rightarrow A^{(Z-1)+} + h\nu$$

recombination coefficient

$$\alpha_r = \int (V_i - v_e)\sigma(V_i - v_e) f(v_e) d^3 v_e$$

cross section

$$\sigma_n^{RR}(E_k) = 2.10 \cdot 10^{-22} \frac{Z^4 E_{1s}^2}{nE_k \left(Z^2 E_{1s} + n^2 E_k\right)} \, [\mathrm{cm}^2]$$

$$\sigma = A \left(\frac{h\nu_0}{E}\right)^2 \sum_1^{\infty} \frac{1}{n(n^2 + h\nu_0/E)}$$

cross section expression used in simulations

$$\sigma = A\left(\frac{h\nu_0}{E}\right)\left(\ln\sqrt{\frac{h\nu_0}{E}} + 0.1402 + 0.525\left(\frac{E}{h\nu_0}\right)^{1/3}\right)$$

asymptotic

$$\alpha_{\mathrm{recu}} := 3.02 \cdot 10^{-19} \frac{\mathrm{m}^3}{\mathrm{s}} \cdot \frac{Z^2}{\sqrt{T_{\mathrm{eff}}}} \cdot \left[\ln\left(\frac{11.32Z}{\sqrt{T_{\mathrm{eff}}}}\right) + 0.14\left(\frac{T_{\mathrm{eff}}}{Z^2}\right)^{\frac{1}{3}}\right]$$

Recombination with un-magnetized electron beam

Potential problem of Non-Magnetized cooling approach is recombination because now we have very small electron transverse temperatures of the order of

Teff: about 0.2-0.5 eV.

$$\alpha_{recu} := 3.02\cdot 10^{-19}\,\frac{m^3}{s}\cdot\frac{Z^2}{\sqrt{T_{eff}}}\cdot\left[\ln\left(\frac{11.32Z}{\sqrt{T_{eff}}}\right) + 0.14\left(\frac{T_{eff}}{Z^2}\right)^{\frac{1}{3}}\right]$$

This can be controlled by helical undulator which introduces coherent azimuthal angle:

$$\theta = \frac{eB\lambda}{2\pi pc}$$

which can produce required T_{eff} to suppress recombination (few eV)

However, this may lead to some reduction in the cooling force by a factor

$$\ln\frac{\rho_{max}}{\rho_{min}} / \ln\frac{\rho_{max}}{r_0}$$

where

$$r_0 = \frac{\theta\lambda}{2\pi}$$

This was checked with VORPAL simulations as part of RHIC-II studies.

Recombination lifetime for LEReC parameters

γ=4.1 (L_{cool}=12m), Q=4 nC,

5.8m rms ion bunch length:

$$\frac{1}{N}\frac{dN}{dt} = -\frac{\alpha_r n_{ei}}{\gamma^2}\frac{l_{cool}}{C}$$

Recombination lifetime >4 hours

γ=10 (L_{cool}=12m), Q=5nC:

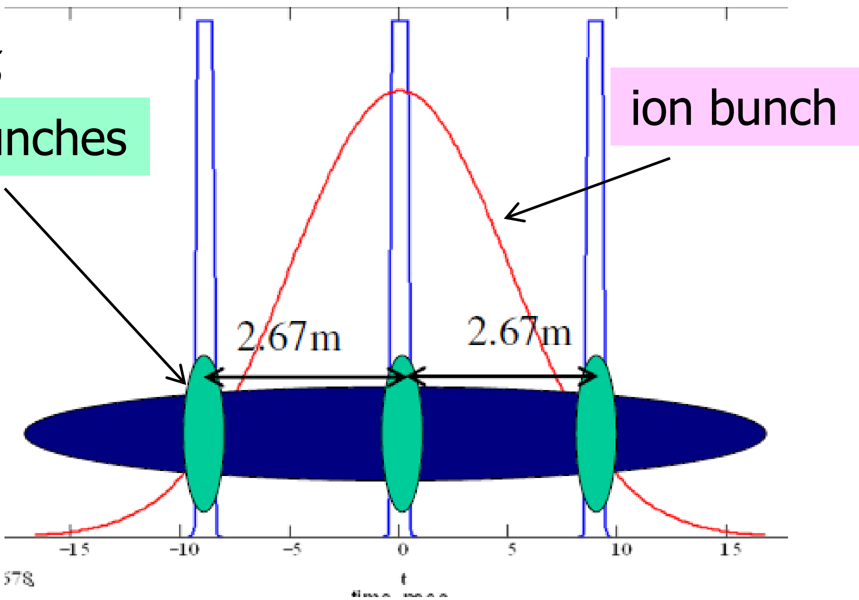
Recombination lifetime=2 hours

(may become noticeable if beam lifetime due to other effects is very good at high energies)

For present LEReC baseline, we do not plan recombination suppression, which should have minor effect on luminosity evolution.

Bunched beam electron cooling

- **First bunched beam electron cooling**

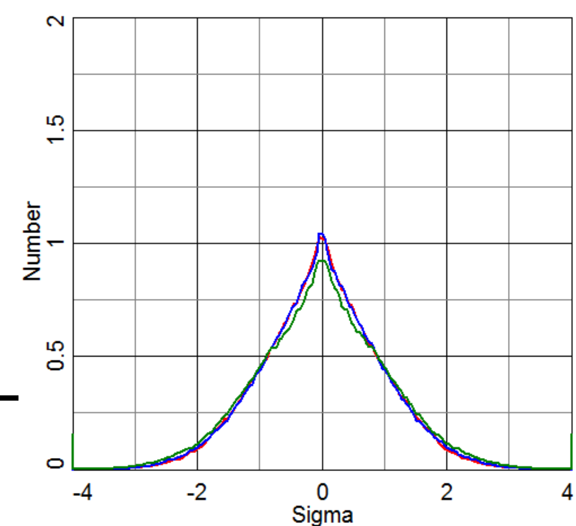


1) Putting a "train" of electron bunches on a single ion bunch.

2) Possibly "painting" through ion bunch length.

- **First electron cooling in a collider:**

  Requires careful control of ion beam distribution under cooling (some advantages of non-magnetized cooling to prevent over cooling (shown in the plot) of beam core).



Some challenges

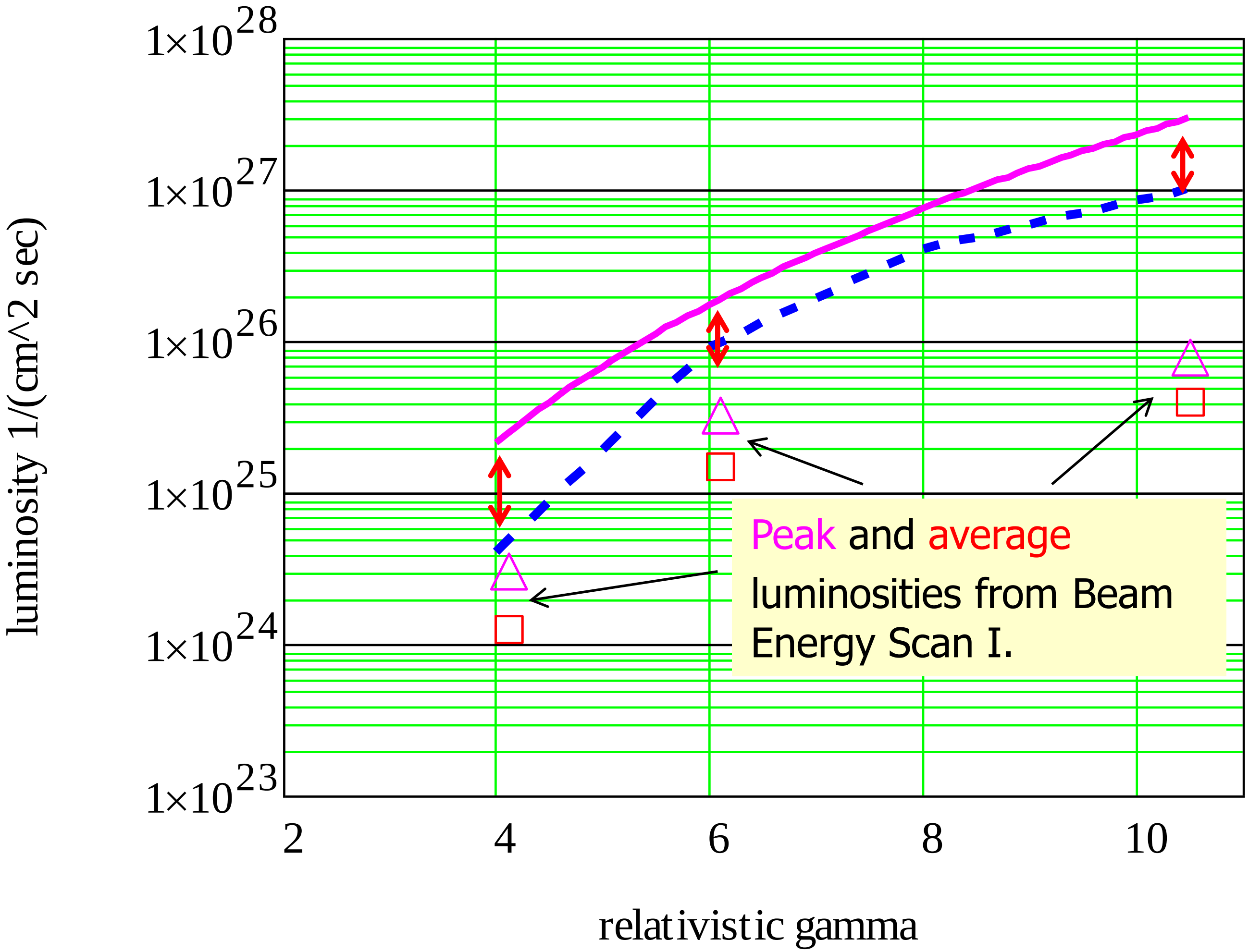
- **Operation in a wide range of energies; control of electron angles in cooling section for all energies.**
- **Use the same electron beam to cool ions in two collider rings: preserving beam quality from one cooling section to another.**
- **Suppression of recombination, if needed; effects on cooling.**
- **Cooling with bunched electron beams.**

Cooling in a collider:

- **Control of ion beam distribution. Do not overcool beam core.**
- **Effects on hadron beam.**
- **Interplay of space-charge and beam-beam in hadrons.**
- **Cooling and beam lifetime (as a result of many effects).**

Luminosity projection for present 28 MHz and new 4.5 MHz RHIC RF systems

C-A/AP/481 (for details)



Expected improvement with electron cooling:

Blue-dash line: possible improvement in average luminosity with present 28 MHz RF.

Magenta: maximum potential improvement in average luminosity (with new RF system).

*achievable luminosity ↕ should be somewhat smaller than indicated by the magenta line because of the uncertainty about beam lifetime due to a combination of various processes.

Summary

- **Electron cooling promises to provide significant luminosity increase for Beam Energy Scan II.**
- **With present 28 MHz RHIC RF, desired 10-fold improvement from cooling could be expected only at highest energies. At lowest energies expected luminosity improvement could be about a factor of 3 only, due to significant transverse acceptance limitation and uncertainty whether beam lifetime will improve if only very weak transverse cooling is allowed due to the space-charge limitation.**
- **Operation with longer bunches allows us to apply significant transverse cooling which should improve beam lifetime at lowest energies and relax space-charge limitations. Thus it offers better path forward towards maximum luminosity gains with cooling.**
- **With long bunches (new low-frequency RF) and cooling one can expect to get closer to a 10-fold increase in luminosity even for lower energy points (exact improvement factor will depend on beam lifetime due to various effects and optimization of 3-D electron cooling in a collider).**